ROBOTICS

CHAPTER 2: ROBOT COMPONENTS

PhD. NGUYỄN HOÀNG GIÁP

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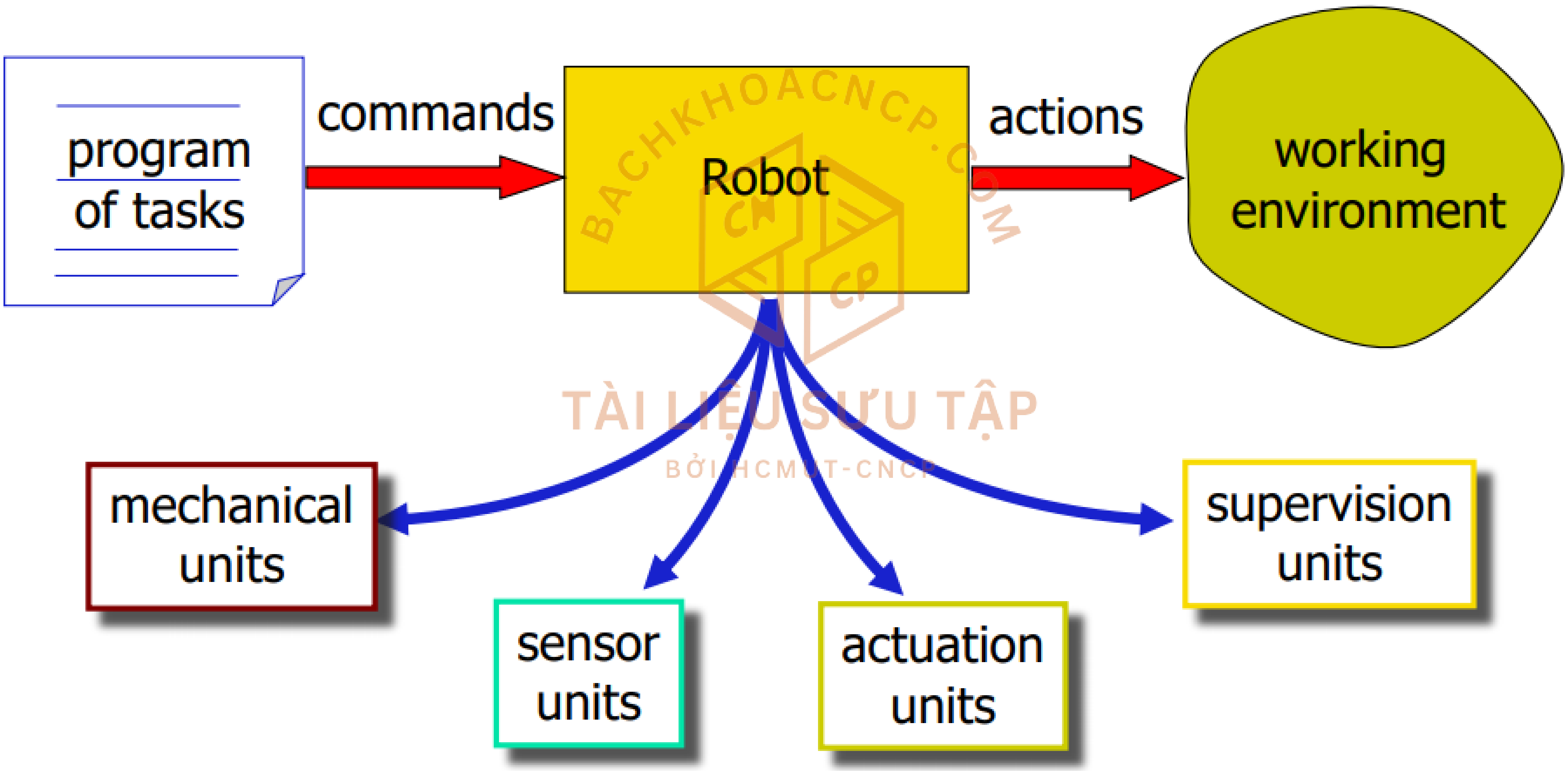
2.1. JOINT ACTUATING SYSTEM

2.2. SENSORS

2.1. JOINT ACTUATING SYSTEM

Robot as a system



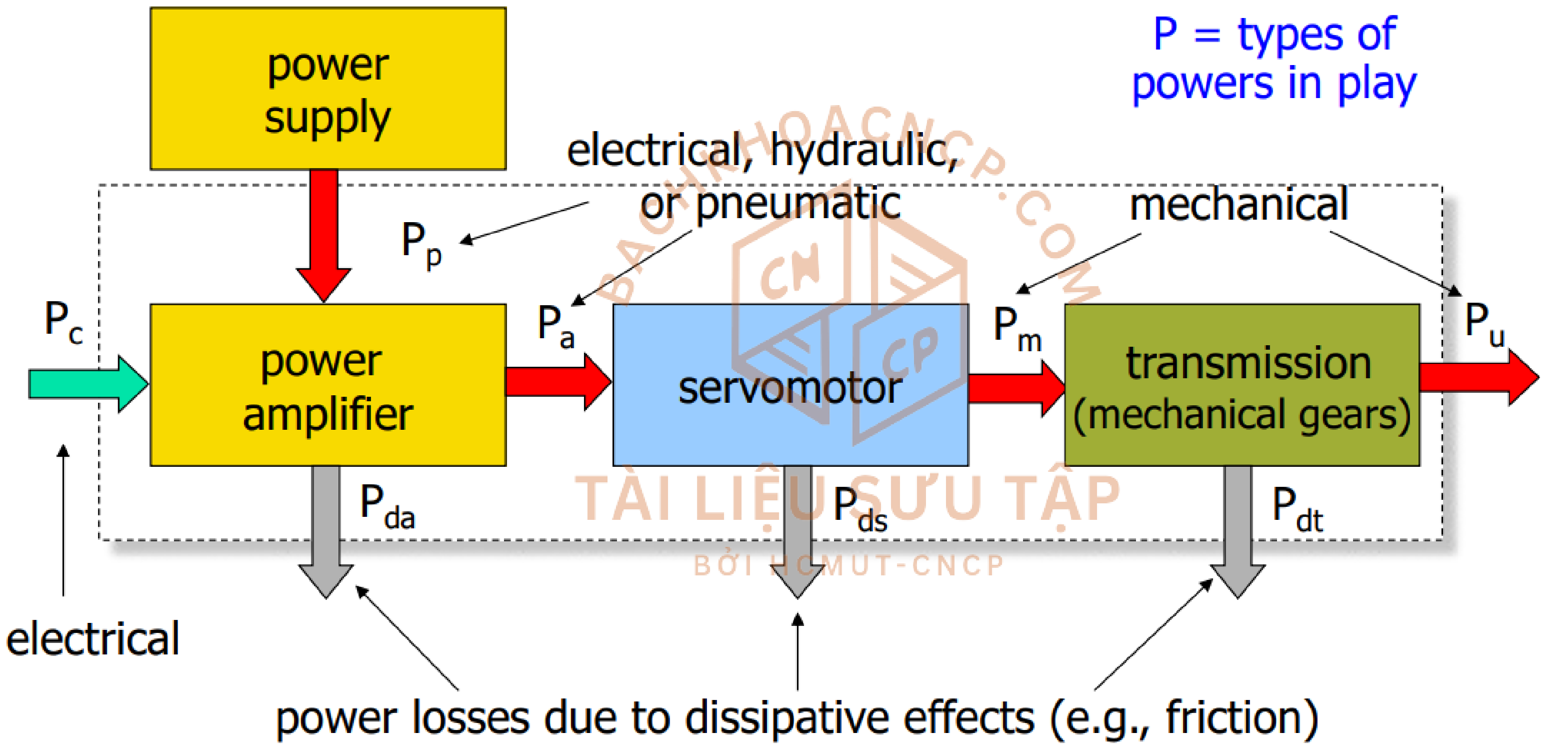
2.1. JOINT ACTUATING SYSTEM

Functional units of a robot

- Mechanical units (robot arms)
  - Rigid links connected through rotational or prismatic joints (each 1 DOF)
  - Mechanical subdivisions: supporting structure (mobility), wrist (dexterity), end-effector (task execution, e.g., manipulation)
- Sensor units
  - Proprioceptive (internal robot state: position and velocity of the joints)
  - Exteroceptive (external world: force and proximity, vision, …)
- Actuation units
  - Motors (electrical, hydraulic, pneumatic)
  - Motion control algorithms
- Supervision units
  - Task planning and control
  - Artificial intelligence and reasoning

2.1. JOINT ACTUATING SYSTEM

Functional units of a robot



Power = Force x Speed = Torque x Angular Speed [Nm/s, W]

Efficiency = PowerOut/PowerIn [%]

2.1. JOINT ACTUATING SYSTEM

Transmissions

- Optimize the transfer of mechanical torque from actuating motors to driven links
- Quantitative transformation (from low torque/high velocity to high torque/low velocity)
- Qualitative transformation (e.g., from rotational motion of an electrical motor to a linear motion of a link along the axis of a prismatic joint)
- Allow improvement of static and dynamic performance by reducing the weight of the actual robot structure in motion (locating the motors remotely, closer to the robot base)

2.1. JOINT ACTUATING SYSTEM

Transmissions in Industrial Robots

- **Spur gears, Helical gear, herringborn gear:** modify direction and/or translate axis of (rotational or translational) motor displacement
  - Problems: deformations, backlash

2.1. JOINT ACTUATING SYSTEM

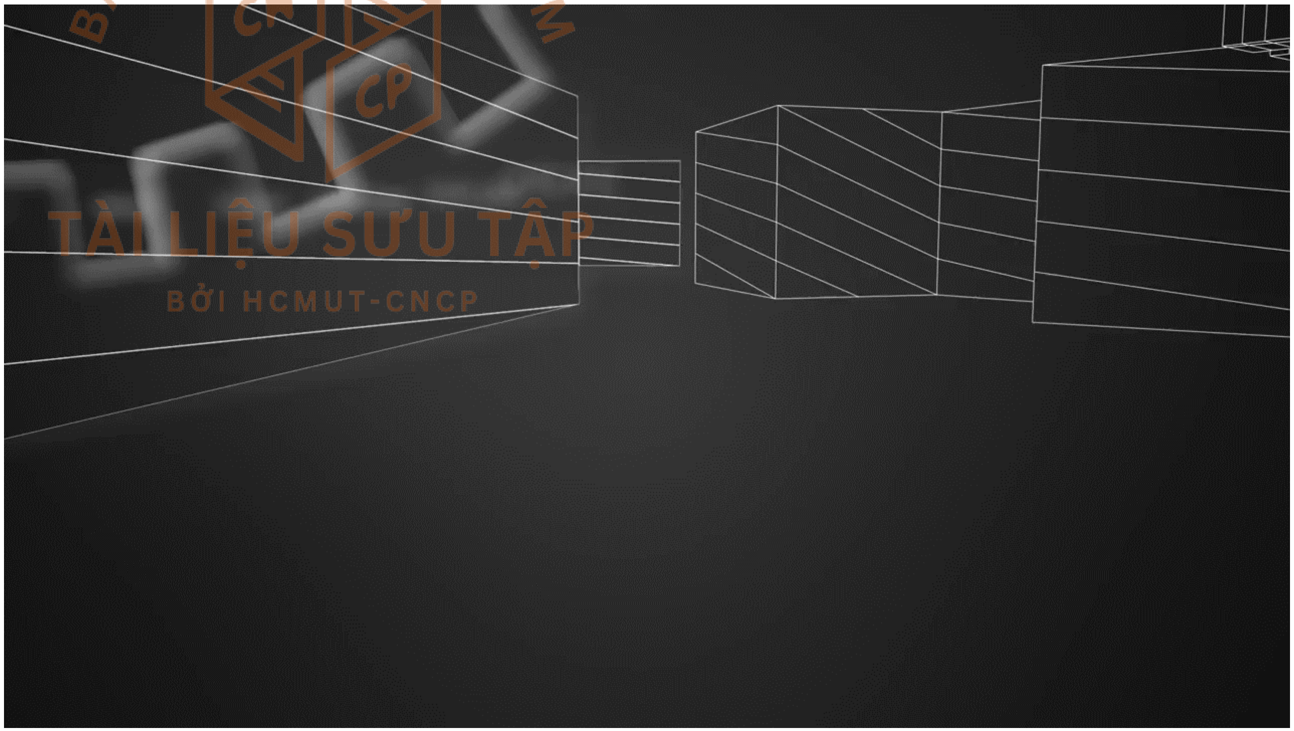
Transmissions in Industrial Robots

- Lead screws: convert rotational into translational motion (prismatic joints)
  - Problems: friction, elasticity, backlash

2.1. JOINT ACTUATING SYSTEM

Transmissions in Industrial Robots

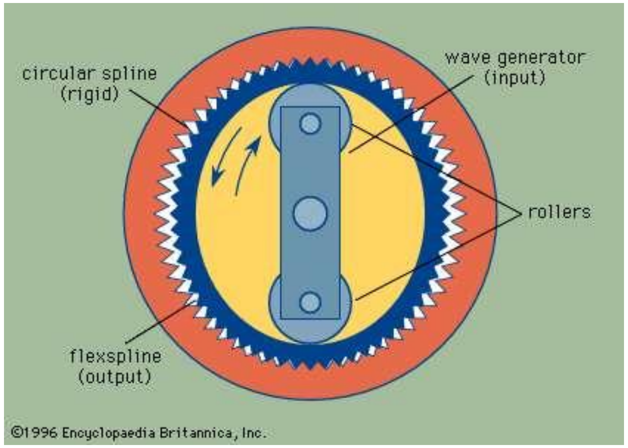
- Toothed belts and chains: dislocate the motor w.r.t. the joint axis
  - Problems: compliance (belts) or vibrations induced by larger mass at high speed (chains)

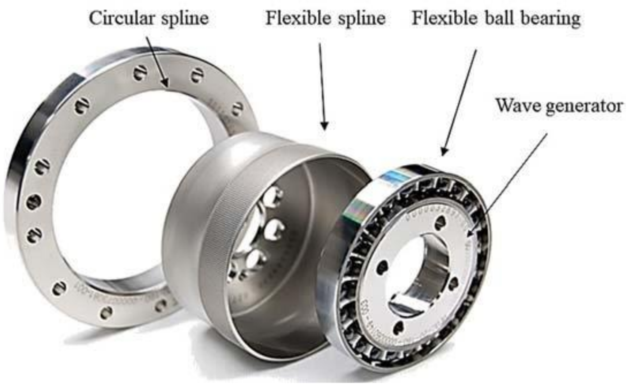


2.1. JOINT ACTUATING SYSTEM

Transmissions in Industrial Robots

- Harmonic drives: compact, in-line, power efficient, with high reduction ratio (up to 150-200:1)
  - Problems: elasticity

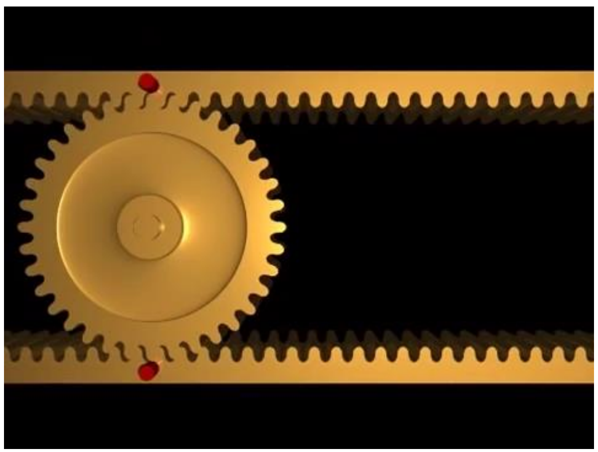




2.1. JOINT ACTUATING SYSTEM

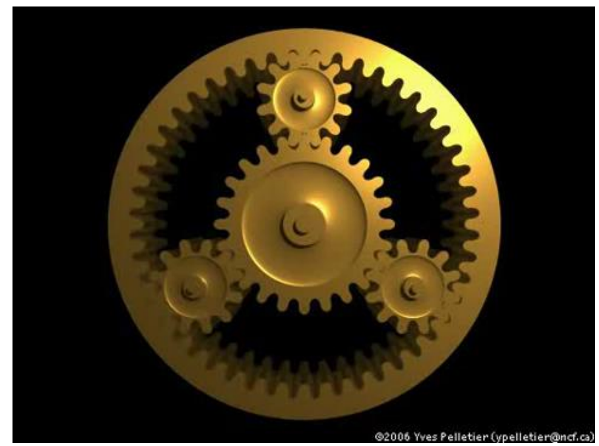
■ Transmissions in Industrial Robots

Rack and Pinion



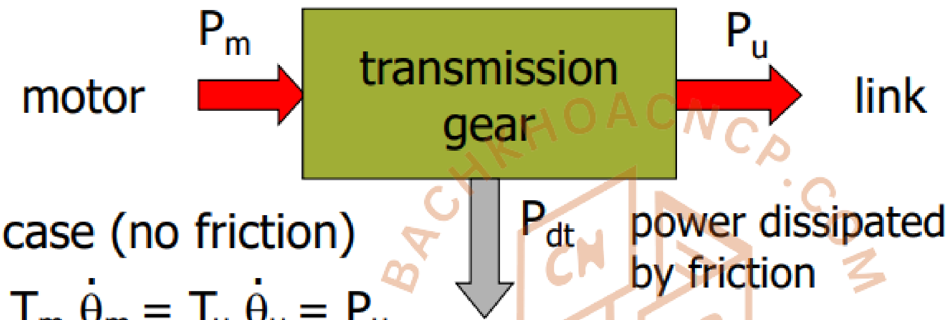
Epi-cycloidal gear train

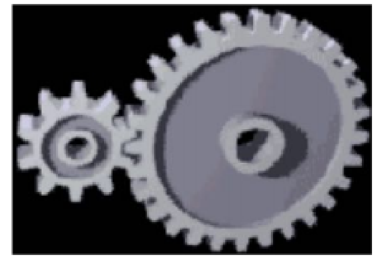
Planetary gear set



2.1. JOINT ACTUATING SYSTEM

Optimal choice of reduction ratio





ideal case (no friction)

$$P_m = T_m \dot{\theta}_m = T_u \dot{\theta}_u = P_u$$

torque × angular speed

n = reduction ratio (≫1) $\quad \dot{\theta}_m = n\,\dot{\theta}_u \Rightarrow T_u = n\,T_m$

to have $\ddot{\theta}_u = a$ (thus $\ddot{\theta}_m = n\,a$), the motor should provide a torque

$$T_m = J_m \ddot{\theta}_m + 1/n\,(J_u \ddot{\theta}_u) = (J_m n + J_u/n)\,a$$

inertia × angular acceleration

for minimizing T_m, we set: $\quad \dfrac{\partial T_m}{\partial n} = (J_m - J_u/n^2)\,a = 0$

$\Rightarrow \boxed{n = (J_u / J_m)^{1/2}}$ "matching" condition between inertias

2.1. JOINT ACTUATING SYSTEM

Inside view on an industrial KUKA robot

2.1. JOINT ACTUATING SYSTEM

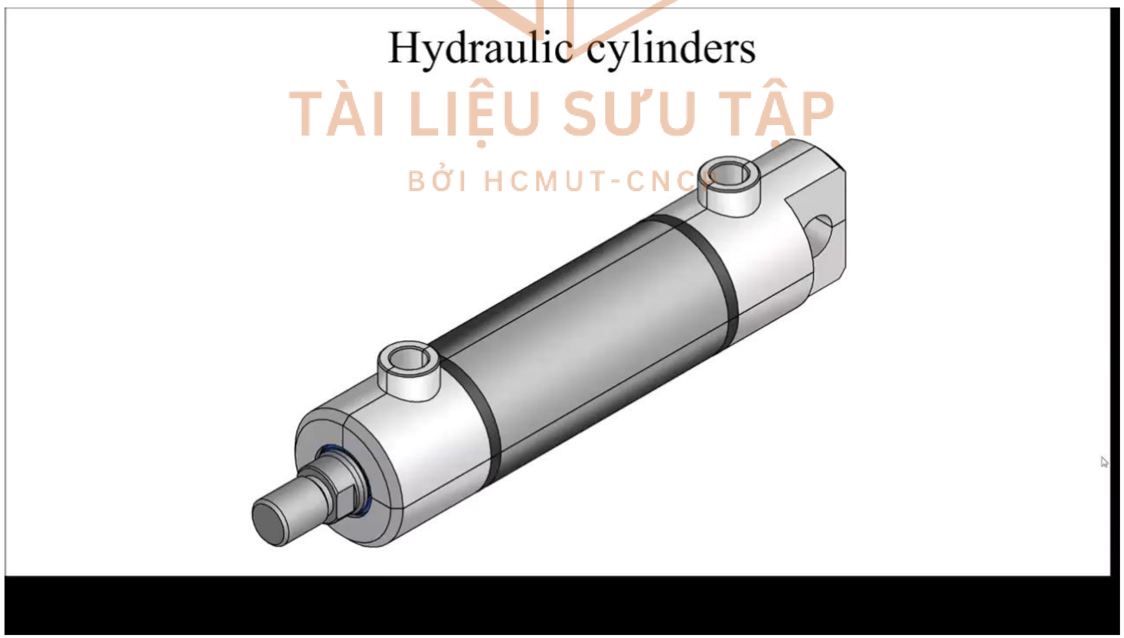
Servo Motors: Pneumatic

- Pneumatic: pneumatic energy (compressor) → pistons or chambers → mechanical energy
  - Difficult to control accurately (change of fluid compressibility) → no trajectory control
  - Used for opening/closing grippers
  - ... or as artificial muscles (McKibben actuators)

2.1. JOINT ACTUATING SYSTEM

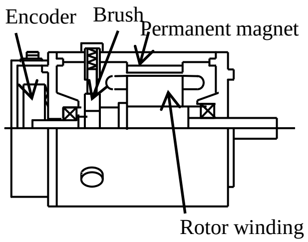
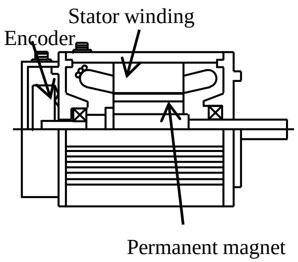
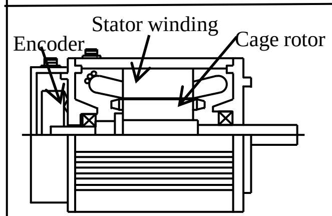
Servo Motors: Hydraulic

- Hydraulic: hydraulic energy (accumulation tank) → pumps/valves → mechanical energy
  - Advantages: no static overheating, self-lubricated, inherently safe (no sparks), excellent power-to-weight ratio, large torques at low velocity (w/o reduction)
  - Disadvantages: needs hydraulic supply, large size, linear motion only, low power conversion efficiency, high cost, increased maintenance (oil leaking)



2.1. JOINT ACTUATING SYSTEM

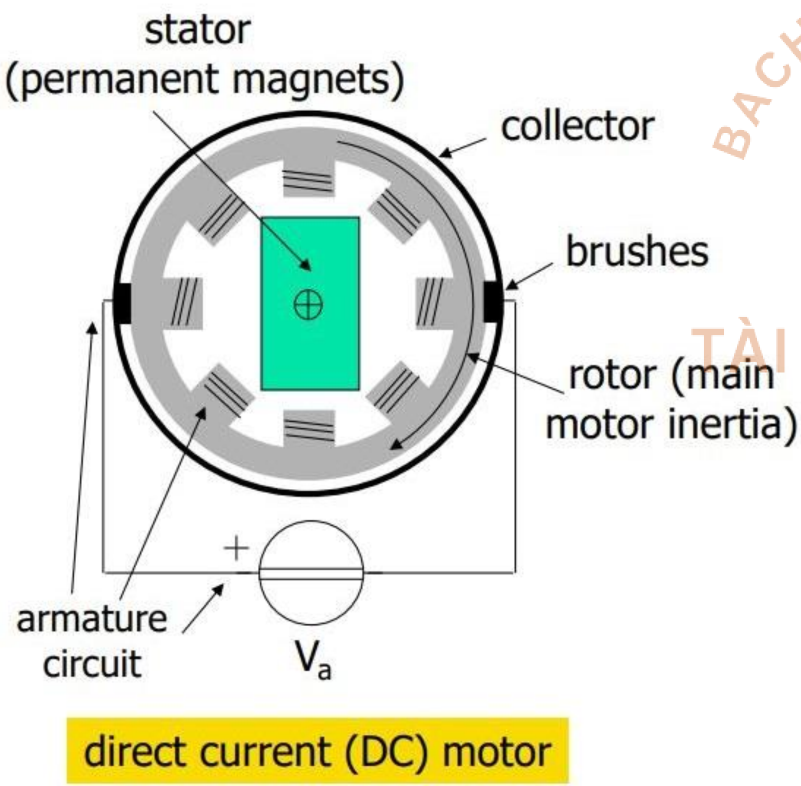
Servo Motors: Electrical Servo Motors

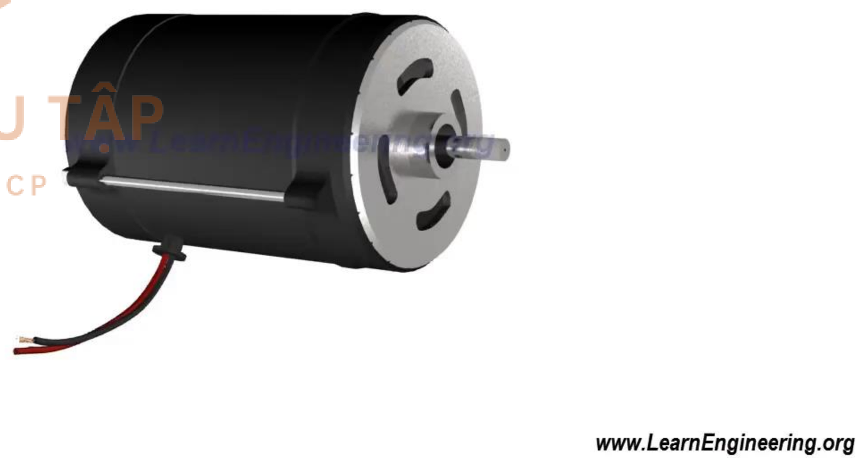
structure	category	Characteristic		Usage
		Advantages	Disadvantages	
	❑DC servo motor	➢Simple control structure ➢High power rate	➢Maintenance required ➢Dust and noise generation ➢Difficult to rotate at high speed	▪ Conveying machine
	❑ Permanent magnet type AC servo motor	➢Convenient maintenance ➢Excellent environmental resistance ➢High efficiency, small size and light weight ➢High power rate	➢Need a position sensor	▪Machine tools ▪robot ▪Industrial machinery ▪Semiconductor equipment
	❑High-speed spindle motor ❑Vector control motor ❑Induction type AC servo motor	➢Convenient maintenance ➢Excellent environmental resistance ➢High speed, large torque ➢The structure is solid	➢Control is complex ➢Low efficiency ➢No electrostatic braking	▪Machine tools ▪Large Plant
	❑ Stepping motor ❑ SRM	➢Simple control structure ➢Small, low cost ➢High stopping torque	➢High torque ripple ➢Low precision ➢High vibration and noise	▪OA / small equipment ▪Conveying machine

2.1. JOINT ACTUATING SYSTEM

Servo Motors: Electrical Servo Motors

❖ Permanent-magnet DC servo motor/ Wound field DC servo motor

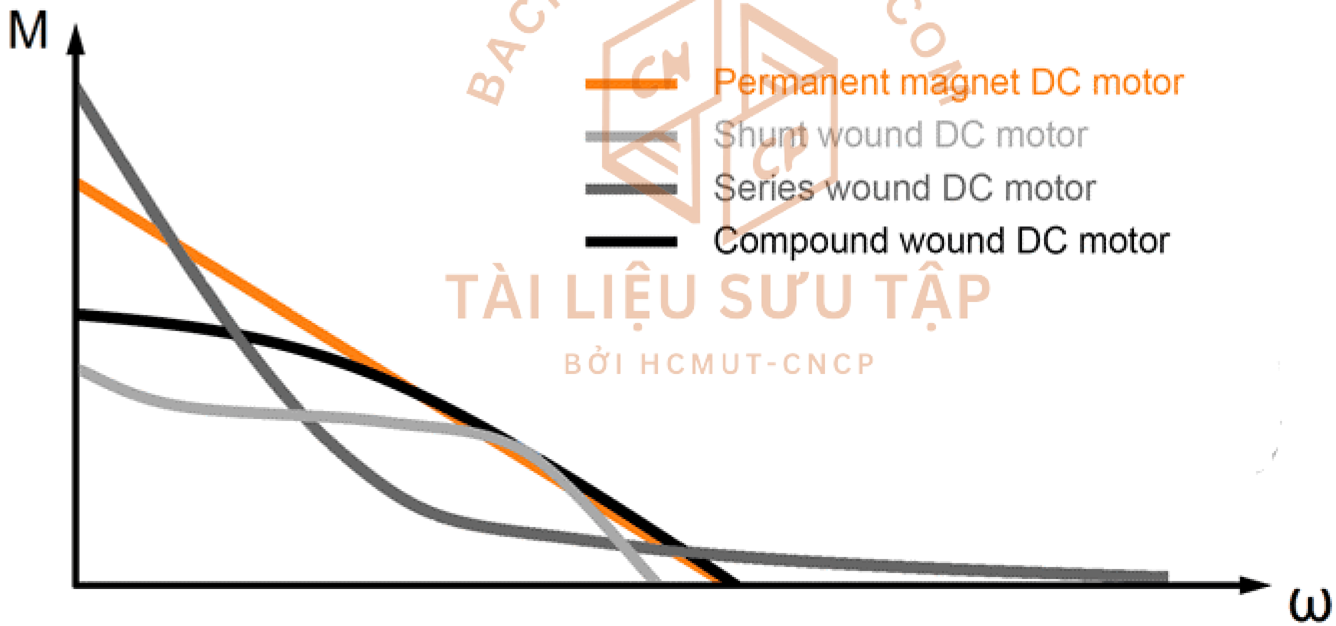




2.1. JOINT ACTUATING SYSTEM

Servo Motors: Electrical Servo Motors

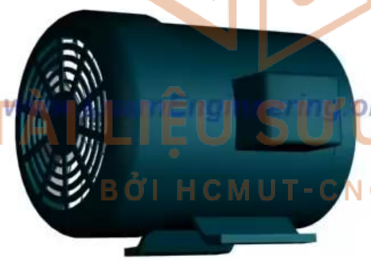
- Permanent-magnet DC servo motor/ Wound field DC servo motor



Torque-speed curves of brushed DC motors

2.1. JOINT ACTUATING SYSTEM

- **Servo Motors:** Permanent Magnet Synchronous Motors



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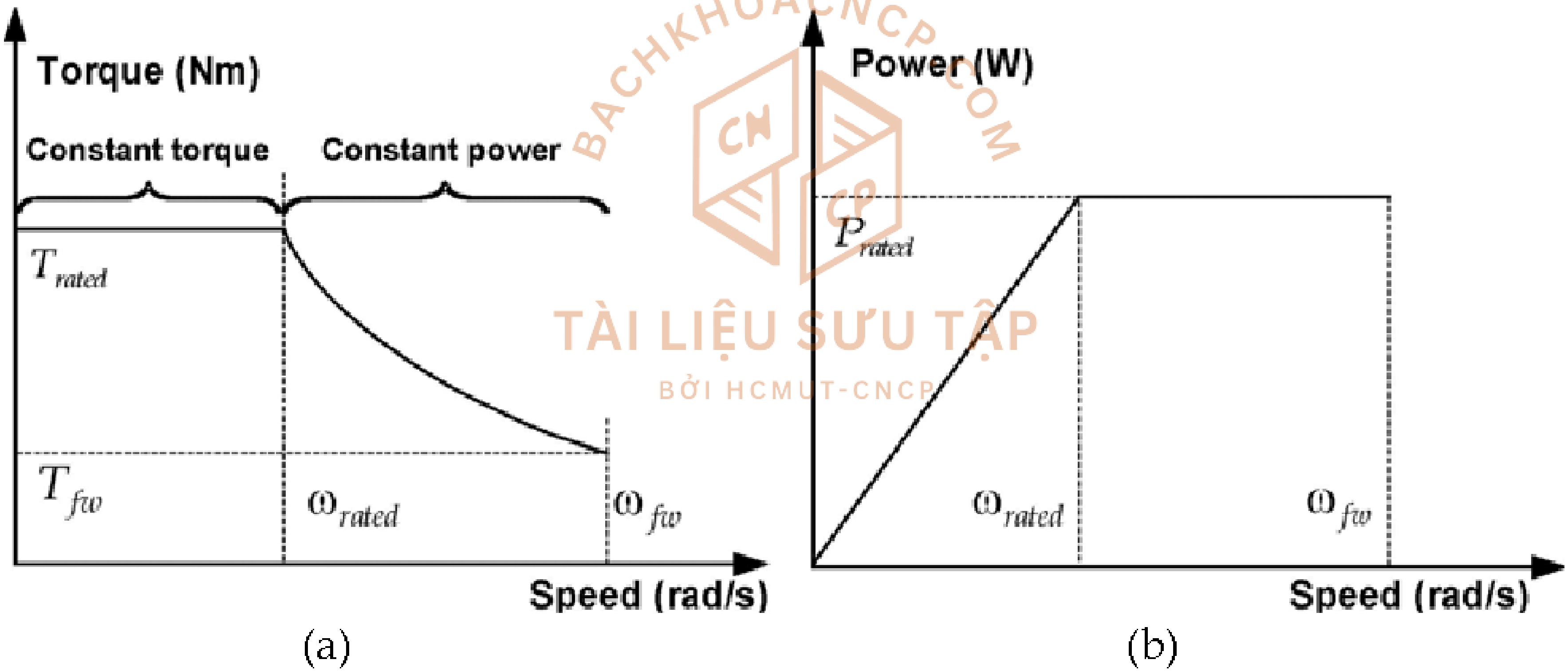
2.1. JOINT ACTUATING SYSTEM

■ Servo Motors: Permanent Magnet Synchronous Motors



2.1. JOINT ACTUATING SYSTEM

■ Servo Motors: AC Induction Motors

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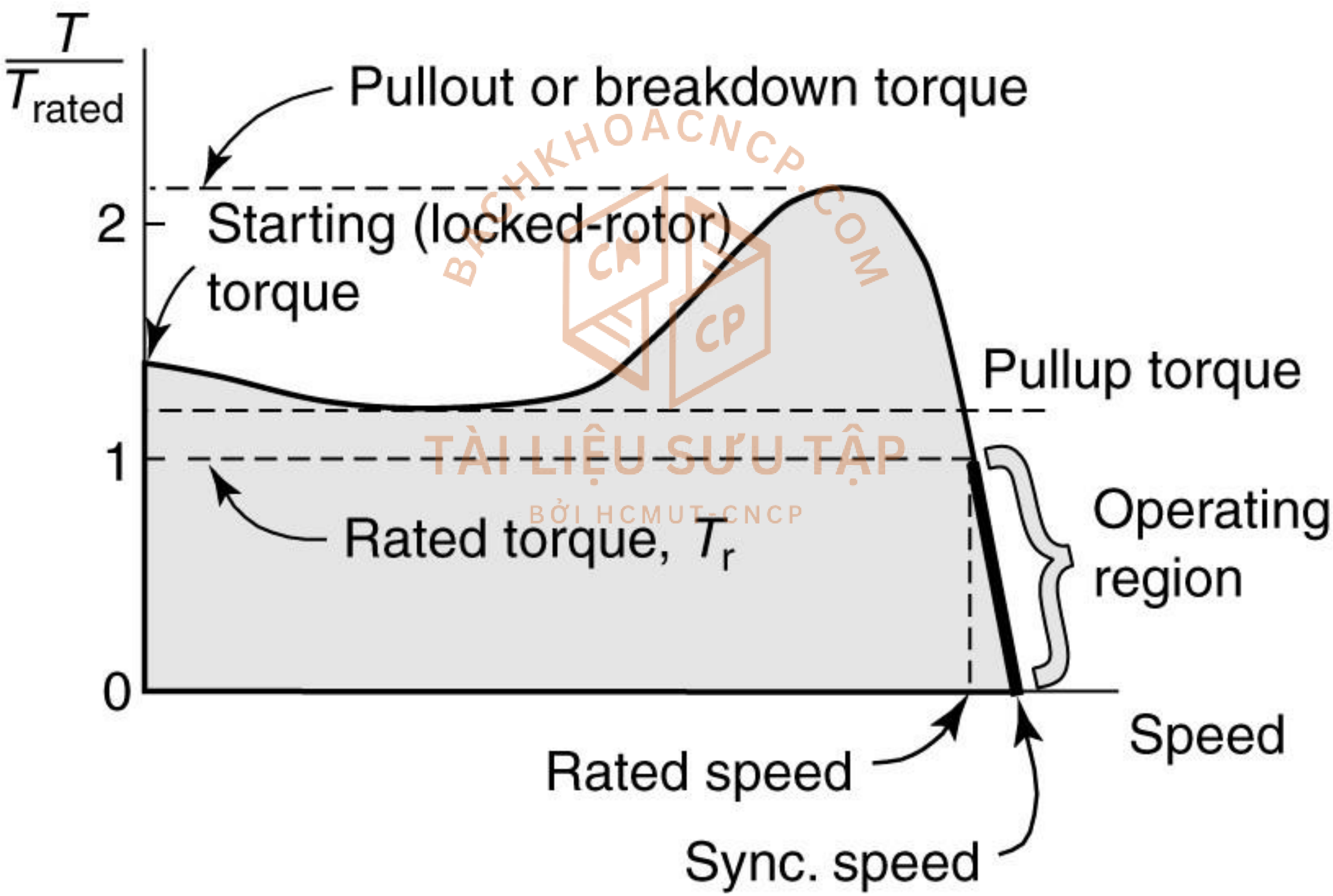
■ Servo Motors: AC Induction Motors



2.1. JOINT ACTUATING SYSTEM

Servo Motors

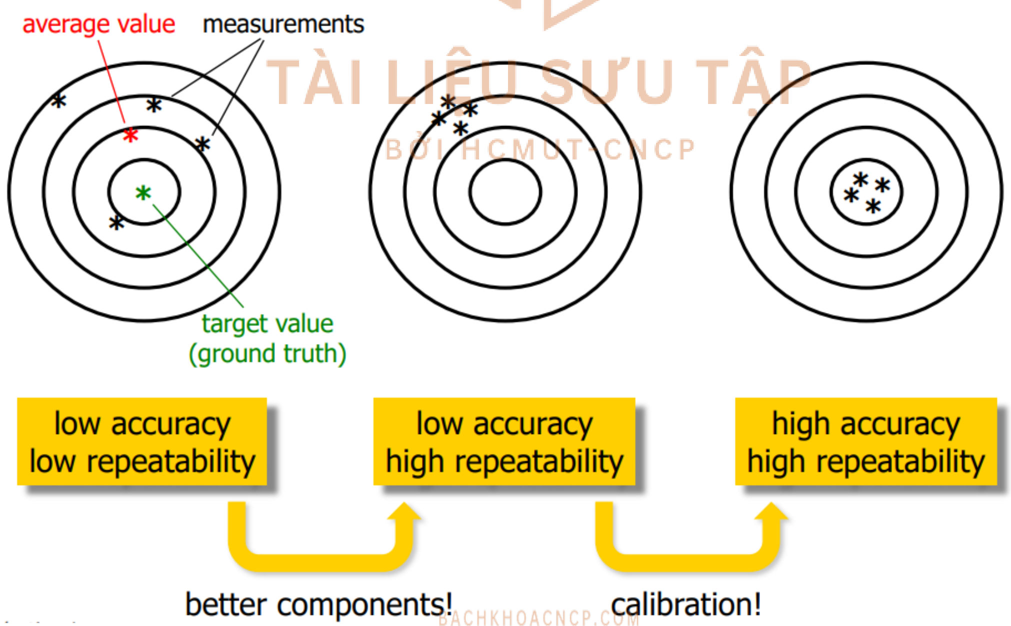
Desired characteristics for robot servo motors:

- Low inertia
- High power-to-weight ratio
- High acceleration capabilities: variable motion regime, with several stops and inversions
- Large range of operational velocities : 1 to 2000 rpm (round per min)
- High accuracy in positioning: at least 1/1000 of a turn
- Low torque ripple: continuous rotation at low speed
- Power: 10W to 10 kW

2.2. SENSORS

Properties of measurement systems

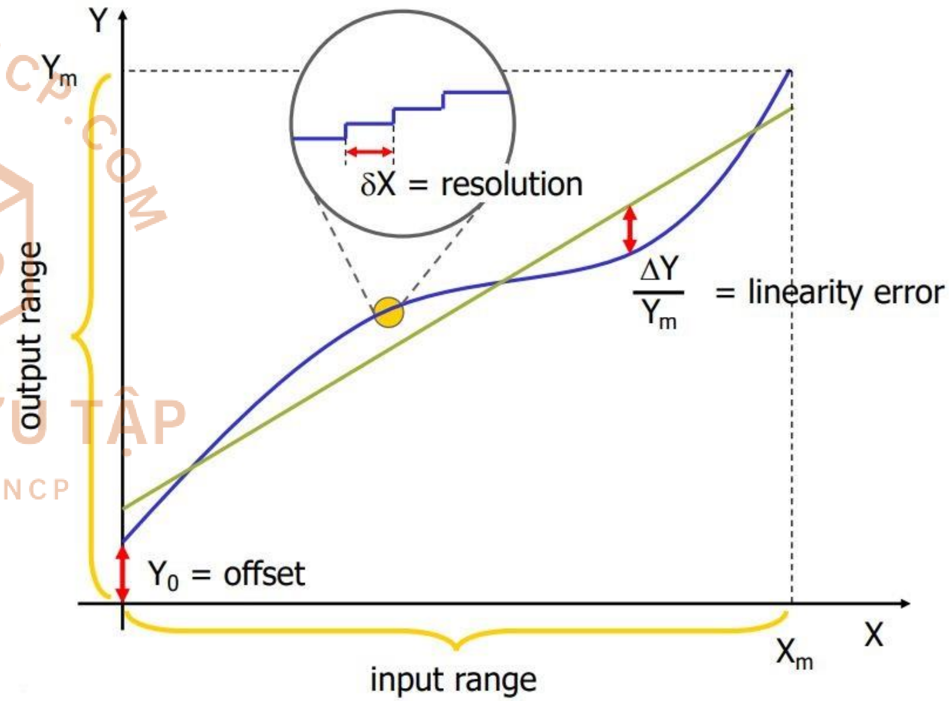
- Accuracy: agreement of measured values with a given reference standard (e.g., ideal characteristics)
- Repeatability: capability of reproducing as output similar measured values over consecutive measurements of the same constant input quantity
- Stability: capability of keeping the same measuring characteristics over time/temperature (similar to accuracy, but in the long run)



2.2. SENSORS

Properties of measurement systems

- Linearity error:
  - Maximum deviation of the measured output from the straight line that best fits the real characteristics
  - As % of the output (measurement) range
- Offset error:
  - Value of the measured output for zero input
  - Sometimes not zero after an operation cycle, due to hysteresis
- Resolution error:
  - Maximum variation of the input quantity producing no variation of the measured output
  - In absolute value or in % of the input range



2.2. SENSORS

Accuracy and Repeatability in Robotics

- Accuracy is how close a robot can come to a given point in its workspace
  - Depends on machining accuracy in construction/assembly of the robot, flexibility effects of the links, gear backlash, payload changes, round-off errors in control computations, ...
  - Can be improved by (kinematic) calibration
- Repeatability is how close a robot can return to a previously taught point
  - Depends only the robot controller/measurement resolution

2.2. SENSORS

Classes of sensors for robots

- Proprioceptive sensors measure the internal state of the robot (position and velocity of joints, but also torque at joints or acceleration of links)
  - Kinematic calibration, identification of dynamic parameters, control
- Exteroceptive sensors measure/characterize robot interaction with the environment, enhancing its autonomy (forces/torques, proximity, vision, but also sensors for sound, smoke, humidity, …)
  - Control of interaction with the environment, obstacle avoidance in the workspace, presence of objects to be grasped, …
  - Mobile-base robots: localization in a map, navigation in unknown environments, …

2.2. SENSORS: PROPRIOCEPTIVE SENSORS

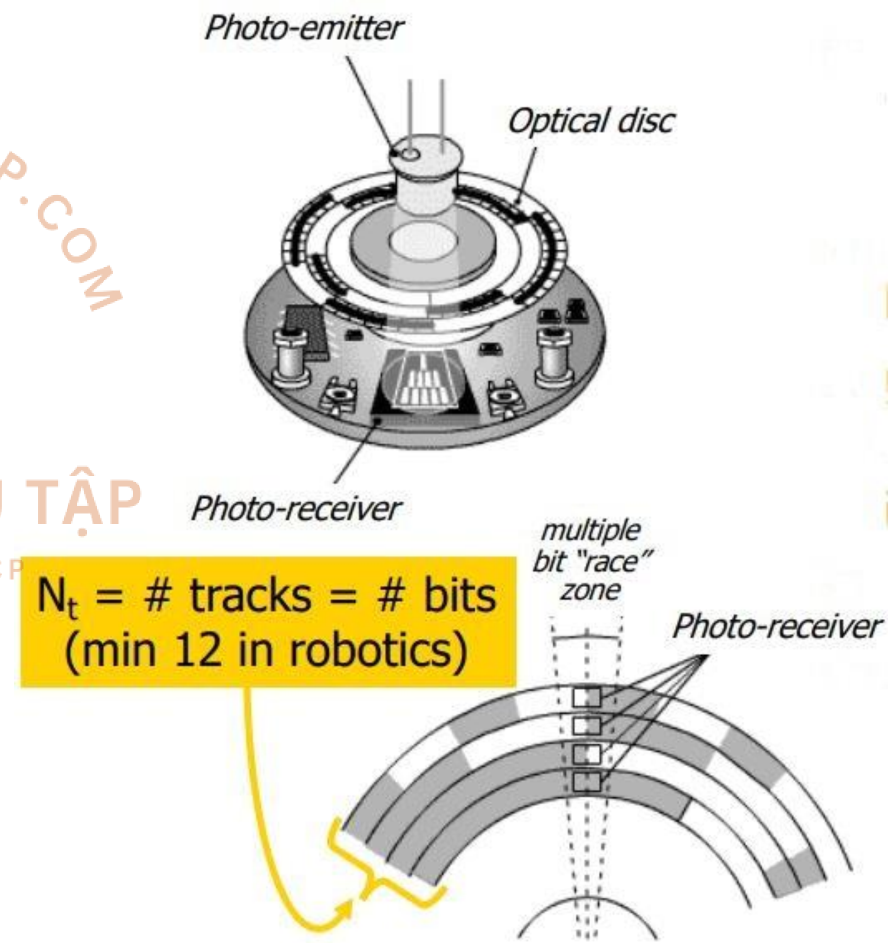
Position Sensors

- Provide an electrical signal proportional to the displacement (linear or angular) of a mechanical part with respect to a reference position
- Linear displacements: potentiometers, linear variable differential transformers (LVDT), inductosyns
- Angular displacements: potentiometers, resolvers, syncros (all analog devices with A/D conversion), optical encoders (digital), Hall sensors, ...

2.1. SENSORS: PROPRIOCEPTIVE SENSORS

Absolute Encoders

- Rotating optical disk, with alternate transparent and opaque sectors on multiple concentric tracks
- (Infrared) light beams are emitted by leds and sensed by photo-receivers
- Light pulses are converted into electrical pulses, electronically processed and transmitted in output
- Resolution = 360°/ 2Nt
- Digital encoding of absolute position. When the optical disk is rotating fast, the use of binary coding may lead to (large) reading errors, in correspondence to multiple transitions of bits



2.2. SENSORS: PROPRIOCEPTIVE SENSORS

Absolute Encoders

- ❖ Ready to measure at start (no “homing”)
- ❖ Two modes for permanent operation

- when switching off the drive, position parameters are saved on a flash memory (and brakes activated)

- battery for the absolute encoder is always active, and measures position even when the drive is off

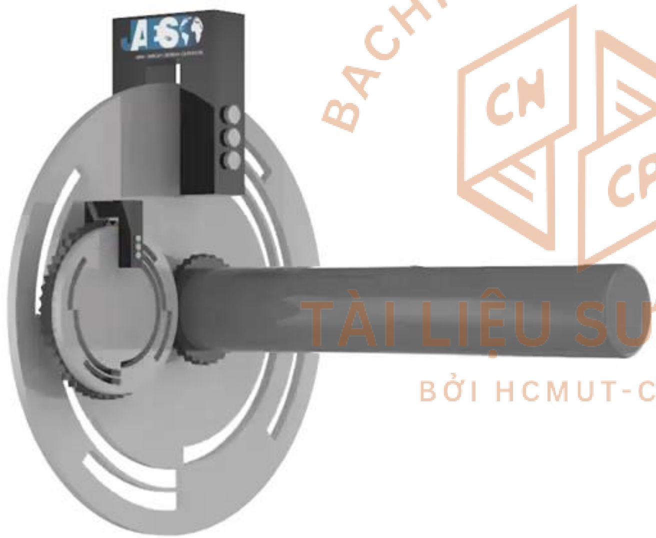
- data memory > 20 years

- ❖ Single-turn or multi-turn versions, e.g.

- 13-bit single-turn has 213 = 8192 steps per revolution (resolution = 0.044o)
- 29-bit multi-turn has 8192 steps/revolution + counts up to 216 = 65536 revolutions

2.2. SENSORS: PROPRIOCEPTIVE SENSORS

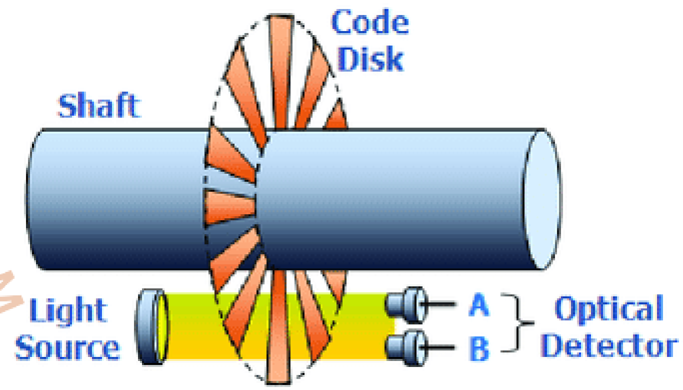
Incremental Encoders



2.2. SENSORS: PROPRIOCEPTIVE SENSORS

Incremental Encoders

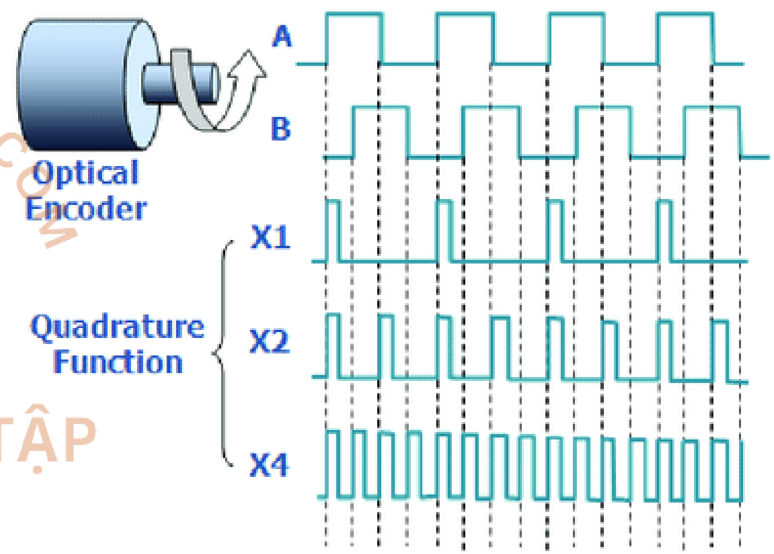
- Optical rotating disk with three tracks, alternating transparent and opaque areas: measures incremental angular displacements by counting trains of Ne pulses ("counts") per turn (Ne = 100÷5000)
- The two A and B tracks (channels) are in quadrature (phase shift of 90° electrical), allowing to detect the direction of rotation
- A third track Z is used to define the "0" reference position, with a reset of the counter (needs "homing" at start)
- Some encoders provide as output also the three phases needed for the switching circuit of brushless motors

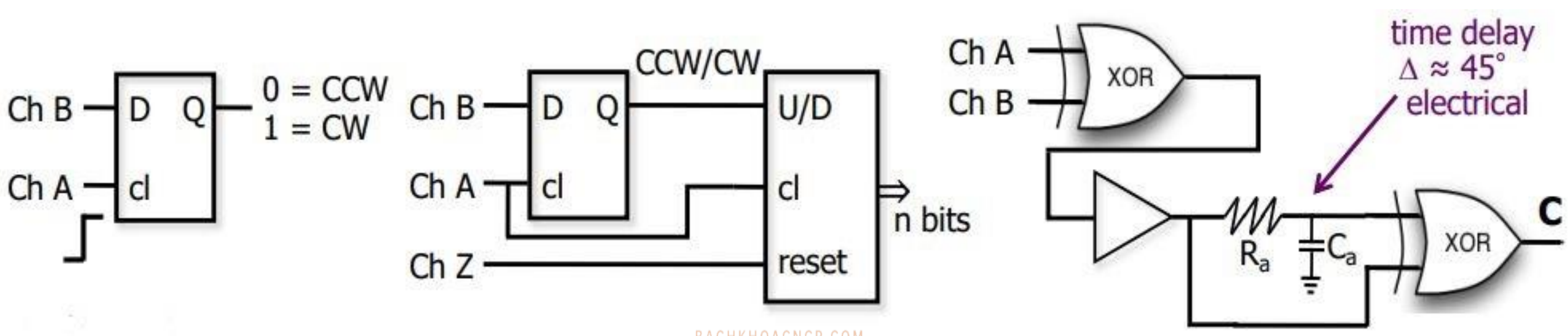


2.2. SENSORS: PROPRIOCEPTIVE SENSORS

Incremental Encoders

- “Fractions of a cycle” of each pulse train are measured in “electrical degrees”
- Signals are fed in a digital counter, with a D-type flip-flop to sense direction + reset
- To improve resolution (4×), the leading and trailing edges of signals A and B are used
- The sequence of pulses C will clock now the counter (increments or decrements)

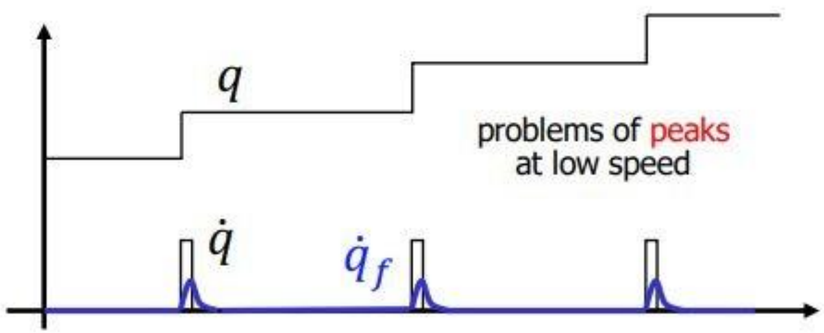


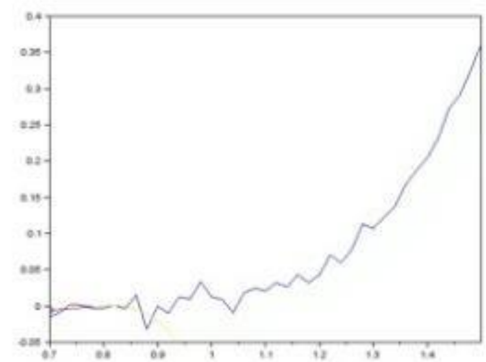


2.2. SENSORS: PROPRIOCEPTIVE SENSORS

Application of position encoders: Indirect measure of velocity

- Numerical differentiation of digital measures of position
  - to be realized on line with Backward Differentiation Formulas (BDFs)
  - 1-step BDF (Euler): $\dot{q}_k = \dot{q}(kT) = \frac{1}{T}(q_k - q_{k-1}) = \frac{\Delta q_k}{T}$
  - 4-step BDF: $\dot{q}_k = \frac{1}{T}\left(\frac{25}{12}q_k - 4q_{k-1} + 3q_{k-2} - \frac{4}{3}q_{k-3} + \frac{1}{3}q_{k-4}\right)$
- Convolution filtering is needed because of noise and position quantization: use of non-causal filters (e.g., Savitzky-Golay) helps, but introduces delays
- Kalman filter for on line state estimation (optimal, assuming Gaussian noise)





animation of Savitzky-Golay filter
with cubic polynomials

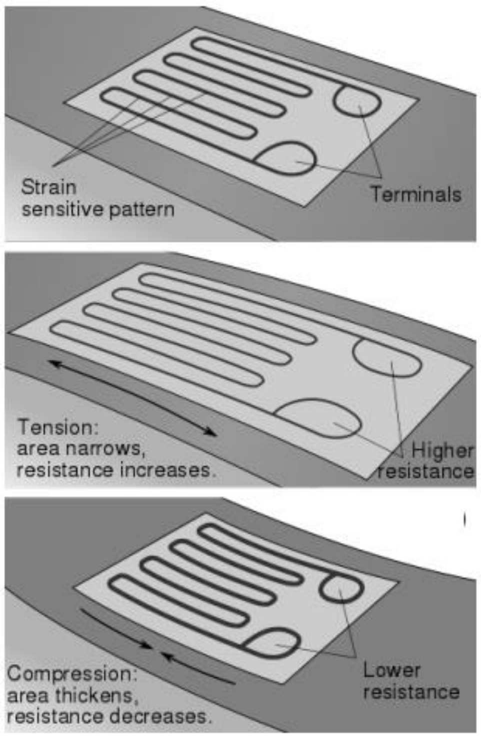
2.2. SENSORS: EXTEROCEPTIVE SENSORS

- FORCE/TORQUE SENSORS
- PROXIMITY/DISTANCE SENSORS
  - Infrared (IF)
  - Ultrasound (US)
  - Laser
  - With structured light
- VISION

2.2. SENSORS: EXTEROCEPTIVE SENSORS

FORCE/TORQUE SENSORS: STRAIN GAUGES

- Indirect information obtained from the measure of deformation of an elastic element subject to the force or torque to be measured
- Basic component is a strain gauge: uses the variation of the resistance R of a metal conductor when its length L or cross-section S vary



2.2. SENSORS: EXTEROCEPTIVE SENSORS

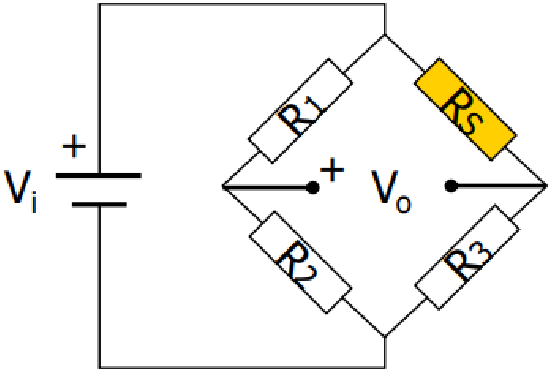
FORCE/TORQUE SENSORS: STRAIN GAUGES

- Principal measurement axis

$$GaugeFactor = GF = \frac{\Delta R/R}{\Delta L/L}$$

(typically GF≈ 2)

- Wheatstone single-point bridge connection(for accurately measuring resistance)
  - R1, R2, R3 very well matched (≈R)
  - RS ≈ R at rest (no stress)
  - Two-point bridges have 2 strain gauges connected oppositely (➚ sensitivity)



- if R1 has the same dependence on T of RS thermal variations are automatically compensated:

$$V_0 = \left(\frac{R_2}{R_1+R_2} - \frac{R_3}{R_3+R_S}\right) V_i$$

2.2. SENSORS: EXTEROCEPTIVE SENSORS

FORCE/TORQUE SENSORS: DAISOCELL

1. FORCE SENSOR (500K-LUGB-D)

- SPEC. -

- Capacity : 5000 N (500 kgf)
- Rated Output : 2.0 mv/v ± 0.5 %
- Input Resistance : 420 Ω ± 5 %
- Output Resistance : 350 Ω ± 1 %
- Zero Balance : ± 2.0 % R.O.
- Temperature Effect on Zero Balance : ±0.03%R.O./10˚C
- Temperature Effect on Rated Output : ±0.03%Load/10˚C
- Compensated Temp. Range : -10 ~ 70 ˚C
- Nonlinearity : 0.20 % R.O.
- Hysteresis : 0.20 % R.O.
- Excitation Recommended : 10 V DC
- Input : Red(+), White(-) : 24 V DC

Output : Green(+), Black(-) : ± 10 V DC

2. FORCE SENSOR (200K-CUG-K)

-SPEC.-

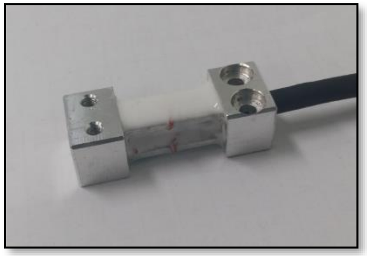
- Capacity : 2000 N (200 kgf)
- Rated Output : Appro. 2.0 mv/v
- Input Resistance : 400 Ω ± 5 %
- Output Resistance : 350 Ω ± 1 %
- Zero Balance : ± 2.0 % R.O.
- Temperature Effect on Zero Balance : ±0.03%R.O./10˚C
- Temperature Effect on Rated Output : ±0.03%Load/10˚C
- Compensated Temp. Range : -10 ~ 70 ˚C
- Nonlinearity : 0.10 % R.O.
- Hysteresis : 0.05 % R.O.
- Excitation Recommended : 10 V DC
- Input : Red(+), White(-)``

Output : Green(+), Black(-)

2.2. SENSORS: EXTEROCEPTIVE SENSORS

FORCE/TORQUE SENSORS: DAISOCELL

3. FORCE SENSOR (10K-BSM)



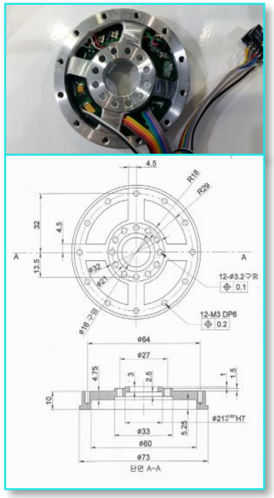
-SPEC.-

- Capacity : 100 N (10 kgf)
- Rated Output : Appro. 2.0 mv/v
- Input Resistance : 350 Ω ± 5 %
- Output Resistance : 350 Ω ± 1 %
- Zero Balance : ± 2.0 % R.O.
- Temperature Effect on Zero Balance : ±0.03%R.O./10˚C
- Temperature Effect on Rated Output : ±0.03%Load/10˚C
- Compensated Temp. Range : -10 ~ 70 ˚C
- Nonlinearity : 0.50 % R.O.
- Hysteresis : 0.20 % R.O.
- Excitation Recommended : 10 V DC
- Input : Red(+), White(-)
  Output : Green(+), Black(-)

2.2. SENSORS: EXTEROCEPTIVE SENSORS

FORCE/TORQUE SENSORS: DAISOCELL

1. TORQUE SENSOR (150N-TS)



-SPEC.-

- Capacity : 150 Nm (1500 kgf.cm)
- Rated Output : 1.50 mv/v ± 2.0 %
- Input Resistance : 350 Ω ± 5 %
- Output Resistance : 350 Ω ± 1 %
- Zero Balance : ± 2.0 % R.O.
- Temperature Effect on Zero Balance : ±0.03%R.O./10˚C
- Temperature Effect on Rated Output : ±0.03%Lo ad/10˚C
- Compensated Temp. Range : -10 ~ 70 ˚C
- Nonlinearity : 0.50 % R.O.
- Hysteresis : 0.50 % R.O.
- Excitation Recommended : 10 V DC
- Input : Red(+), White(-)

Output : Green(+), Black(-)

2. TORQUE SENSOR (100N-TS)

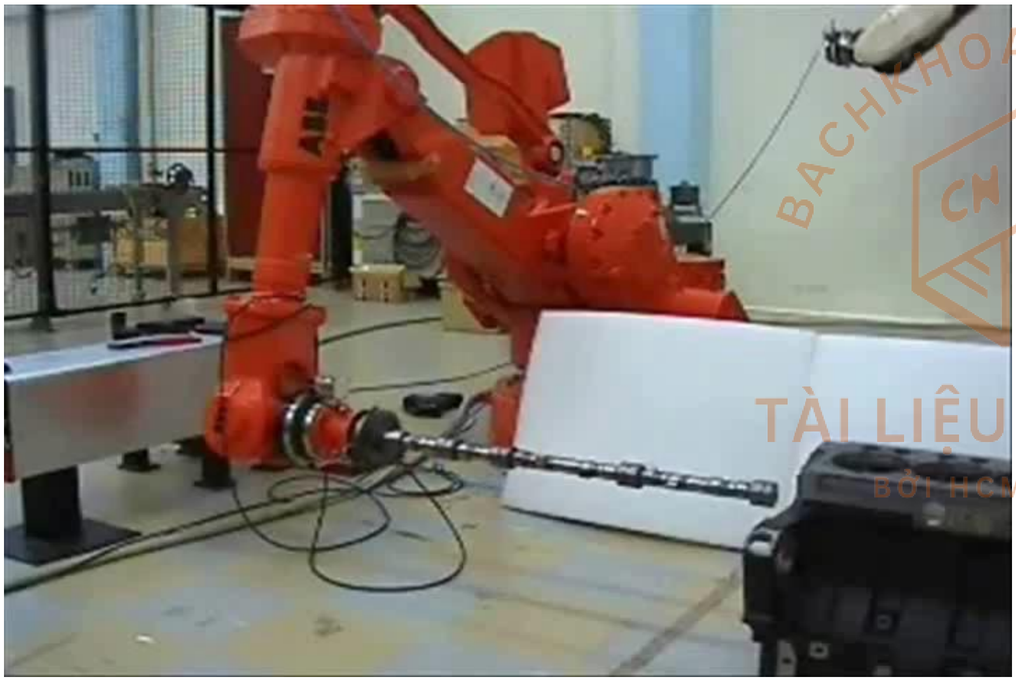
-SPEC.-

- Capacity : 100 Nm (1500 kgf.cm)
- Rated Output : 1.50 mv/v ± 2.0 %
- Input Resistance : 350 Ω ± 5 %
- Output Resistance : 350 Ω ± 1 %
- Zero Balance : ± 2.0 % R.O.
- Temperature Effect on Zero Balance : ±0.03%R.O./10˚C
- Temperature Effect on Rated Output : ±0.03%Load/10˚C
- Compensated Temp. Range : -10 ~ 70 ˚C
- Nonlinearity : 0.90 % R.O.
- Hysteresis : 0.50 % R.O.
- Excitation Recommended : 10 V DC
- Input : Red(+), White(-)

Output : Green(+), Black(-)

2.2. SENSORS: EXTEROCEPTIVE SENSORS

FORCE/TORQUE SENSORS: APPLICATIONS



UNIPULSE

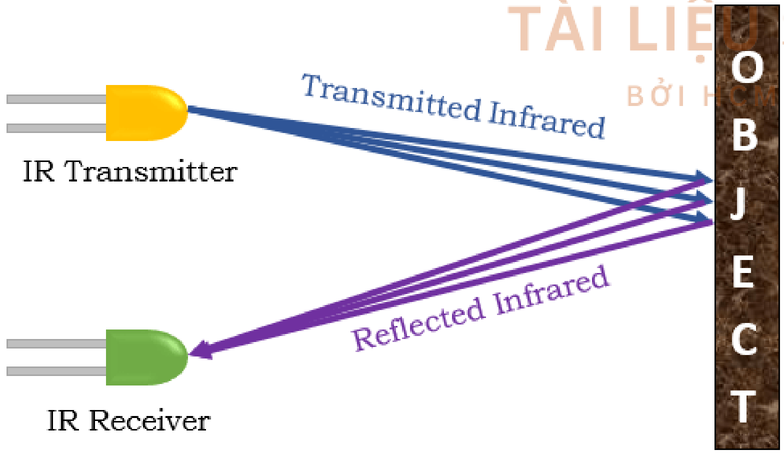
2.2. SENSORS: EXTEROCEPTIVE SENSORS

FORCE/TORQUE SENSORS: APPLICATIONS

2.2. SENSORS: EXTEROCEPTIVE SENSORS

PROXIMITY/DISTANCE SENSOR

- Infrared: a light source (LED) emitting a ray beam (at 850±70 nm) which is then captured by a receiver (photo-transistor), after reflection by an object
- Received intensity is related to distance
  - narrow emitting/receiving angle; use only indoor; reflectance varies with object color
- Typical sensitive range: 4÷30 cm or 20÷150 cm

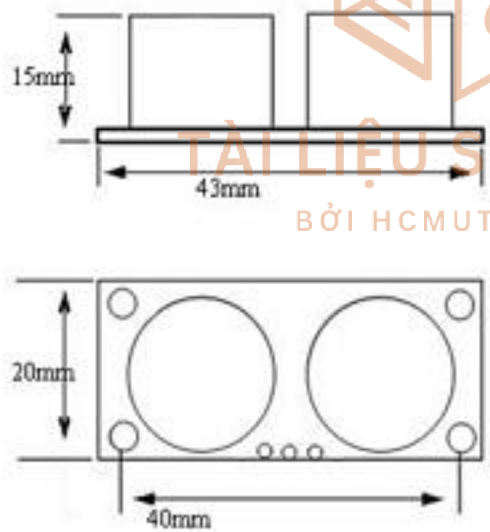


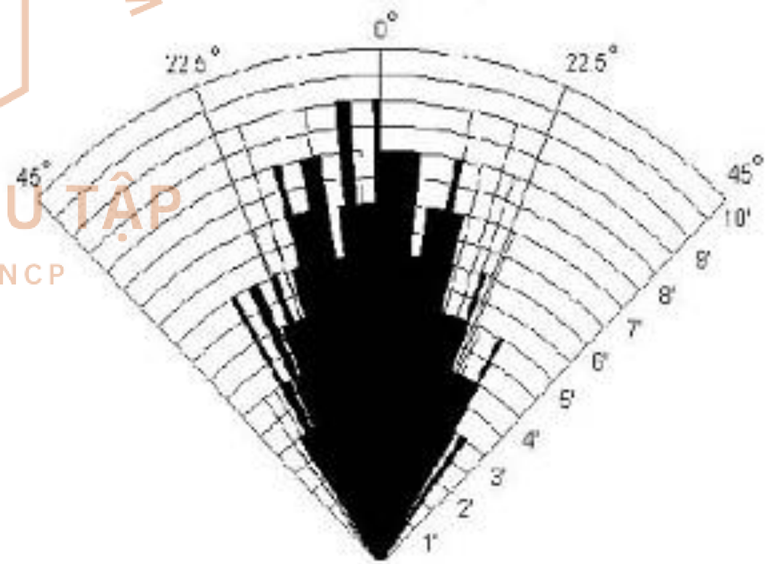
SHARP GP2YOA41SK0F 4-30cm Optical sensor 5V

2.2. SENSORS: EXTEROCEPTIVE SENSORS

ULTRASOUND SENSOR

- Use of sound wave propagation and reflection (at > 20 kHz, mostly 50 kHz), generated by a piezoelectric transducer excited by alternate voltage
- Distance is proportional to the Time-Of-Flight (TOF) along the sensor-object-sensor path





Practical test of performance.

Best in 30 degree angle

2.2. SENSORS: EXTEROCEPTIVE SENSORS

ULTRASOUND SENSOR: APPLICATION

Robotic Mapping with Ultrasonic Sensor

2.2. SENSORS: EXTEROCEPTIVE SENSORS

LASER SCANNER

- Two-dimensional scan of the environment with a radial field of infrared laser beams (laser radar)
- Time between transmission and reception is directly proportional to the distance to the object (Time-of-Flight)

SICK 2D LiDAR sensors

Type: **LMS1104C-111031S01**
Product family: LMS1000
Product family group: 2D LiDAR sensors
•**Working range:** 0.2 m ... 64 m
•**Aperture angle:** Horizontal (275°)
•**Enclosure rating:** IP65, IP67
•**Color:** Gray (RAL 7042)
•**Integrated application:** Integrated field evaluation with flexible fields, Data output
•**Electrical connection:** M12 round connectors (D-coded, aligned) with swivel connector
•**Scanning frequency:** 150 Hz, 4 x 37,5 Hz

2.2. SENSORS: EXTEROCEPTIVE SENSORS

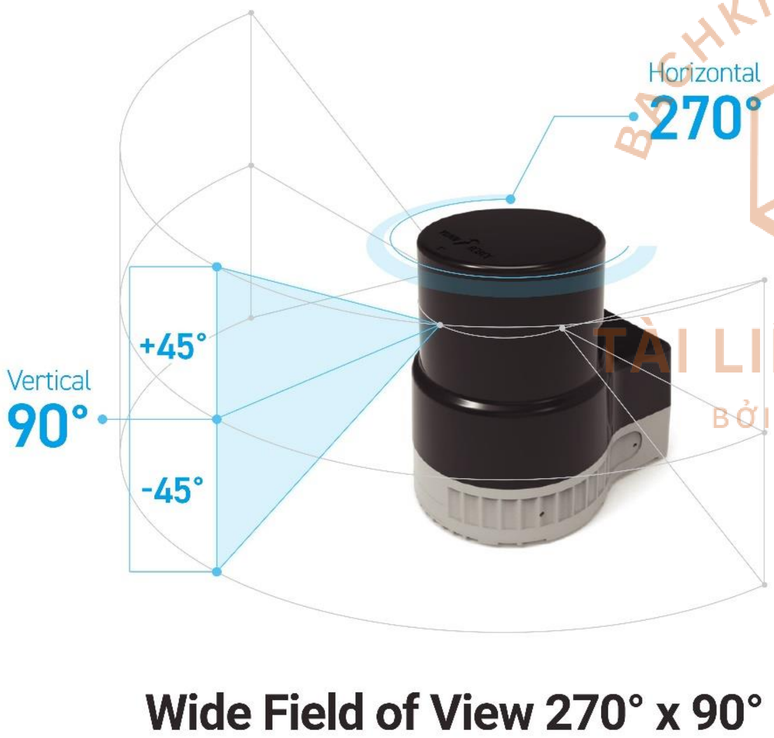
LASER SCANNER

HOKUYO UST-05LN

- 2D scanner for measuring distance between the sensor and its surroundings.
- Supply voltage 10 to 30V
- The smallest and lightest of its kind
- Measurement distance, 5m
- Faster response, 66msec
- More flexible field setting available

2.2. SENSORS: EXTEROCEPTIVE SENSORS

LASER SCANNER



YUJIN YRL3 series

Key Features
•ToF (Time of Flight) Single Channel LiDAR
•Low Cost and Compact
•Wider Field of View : 270˚(Horizontal) x 90˚(Vertical)
•Adjustable Vertical Angle
•ROS Compatible
•Quick, Scalable Software Support

2.2. SENSORS: EXTEROCEPTIVE SENSORS

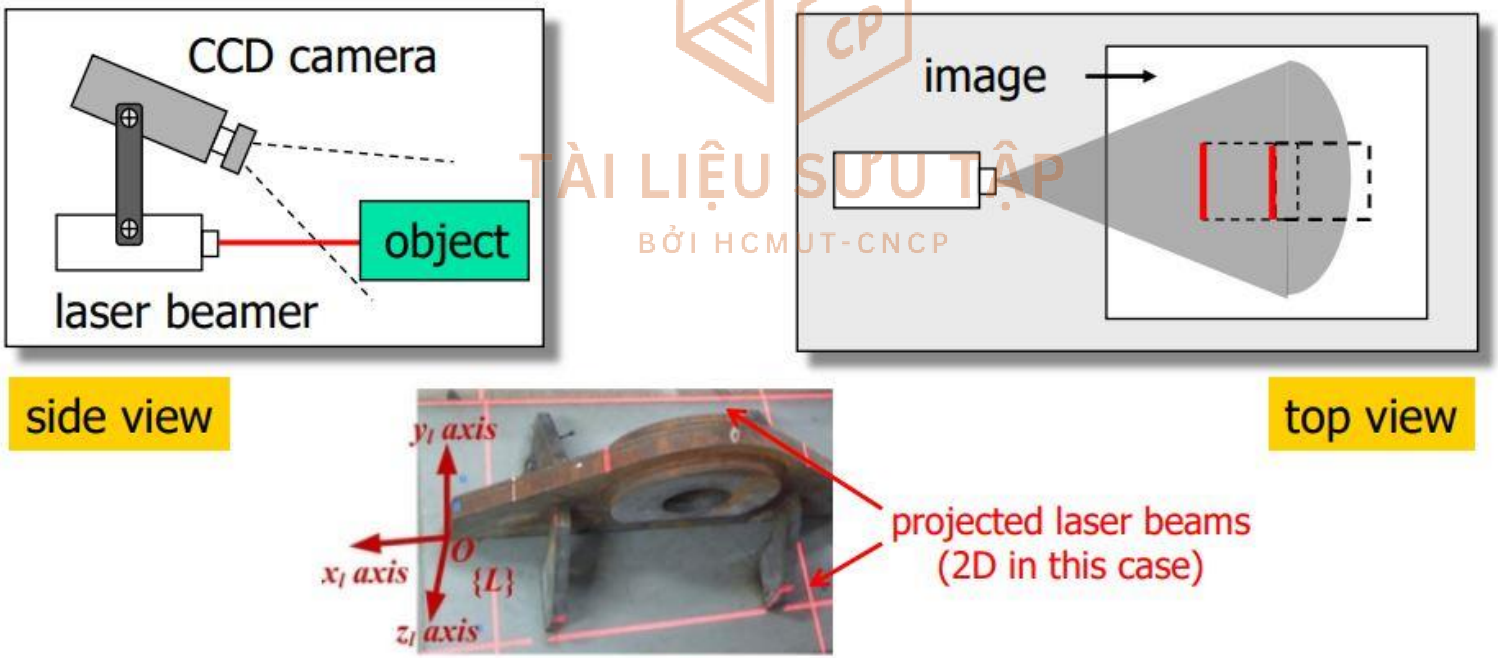
LASER SCANNER: APPLICATION

- **SLAM (Simultaneous Localization and Mapping)** with a laser scanning sensor mounted on a mobile robot
- An “extended” state estimation problem: determine at the same time
  - A map of the environment (sometimes, of its “landmarks” only)
  - The robot location within the map using an incremental, iterative measurement process (large scale data) illustrating the benefit of “loop closure” on long range data (map correction)

2.2. SENSORS: EXTEROCEPTIVE SENSORS

STRUCTURED LIGHT 3D SCANNER

- A **structured light 3D scanner** is a 3D scanning device for measuring the three-dimensional shape of an object using projected light patterns and a camera system
- The position of the "red pixels" on the camera image plane is in trigonometric relation with the object distance from the sensor



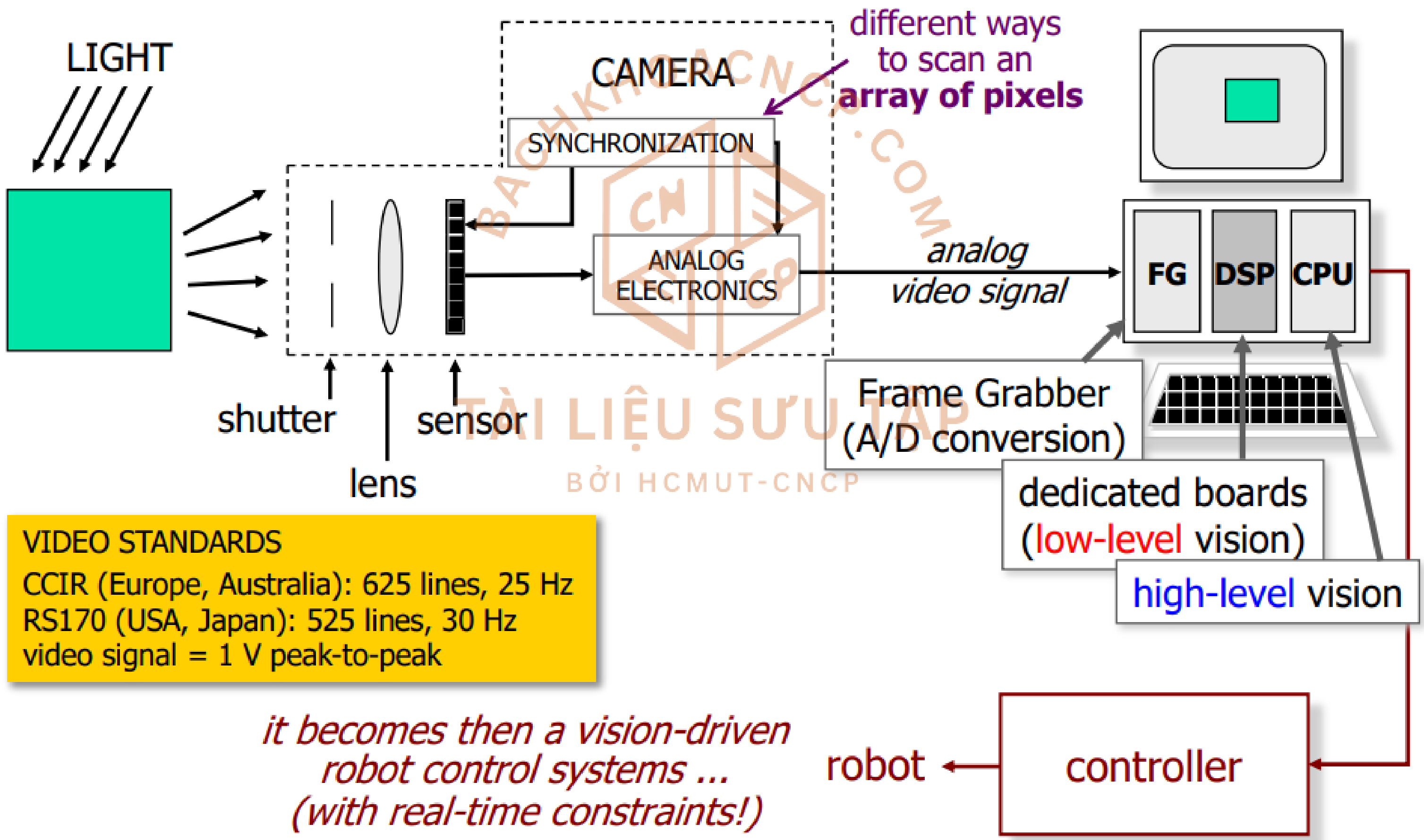
2.2. SENSORS: EXTEROCEPTIVE SENSORS

STRUCTURED LIGHT 3D SCANNER

Automated Laser Scanning Inspection Easily Taught Using Robotiq Plug + Play Solutions

2.2. SENSORS: EXTEROCEPTIVE SENSORS

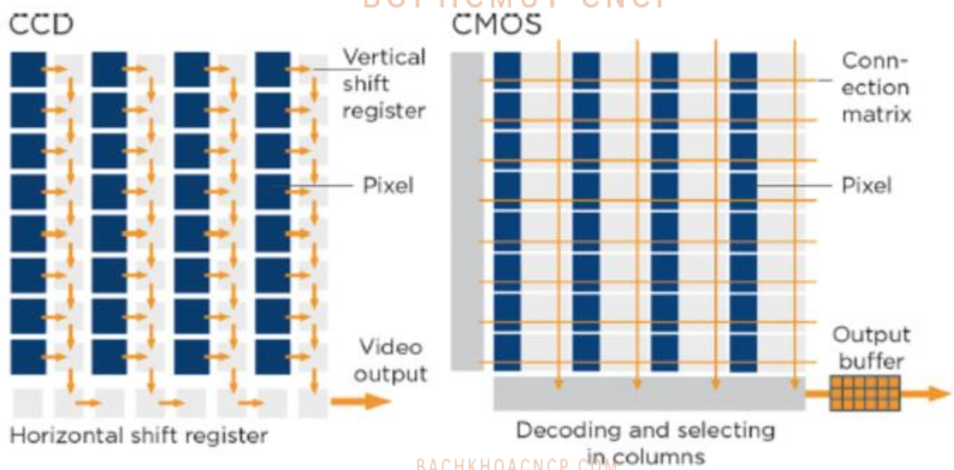
VISION SYSTEMS



2.2. SENSORS: EXTEROCEPTIVE SENSORS

SENSOR FOR VISION

- Arrays (spatial sampling) of photosensitive elements (pixel) converting light energy into electrical energy
- CCD (Charge Coupled Device): each pixel surface is made by a semiconductor device, accumulating free charge when hit by photons (photoelectric effect); “integrated” charges “read-out” by a sequential process (external circuitry) and transformed into voltage levels
- CMOS (Complementary Metal Oxide Semiconductor): each pixel is a photodiode, directly providing a voltage or current proportional to the instantaneous light intensity, with possibility of random access to each pixel



2.2. SENSORS: EXTEROCEPTIVE SENSORS

SENSOR FOR VISION: CMOS VS CCD

- Reduction of fabrication costs of CMOS imagers
- Better spatial resolution of elementary sensors
  - CMOS: 1M pixel, CCD: 768×576 pixel
- Faster processing speed
  - 1000 vs. 25 fps (frames per second)
- Possibility of integrating "intelligent" functions on single chip
  - Sensor + frame grabber + low-level vision
- Random access to each pixel or area
  - Flexible handling of ROI (Region Of Interest)
- Possibly lower image quality w.r.t. CCD imagers
  - Sensitivity, especially for applications with low S/N signals
- Customization for small volumes is more expensive
  - CCD cameras have been since much longer time on the market

2.2. SENSORS: EXTEROCEPTIVE SENSORS

SENSOR FOR VISION

COGNEX Machine Vision Systems